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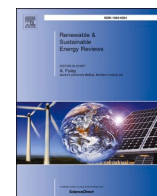
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Making the internet globally sustainable: Technical and policy options for improved energy management, governance and community acceptance of Nordic datacenters

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ABSTRACT

Both policymakers and the technology industry need to do more to combat the ever-growing demand for data and its associated energy impacts. In this study, based on novel corporate data, expert interviews, focus groups with members of the public, extensive site visits across Greenland, Iceland and Norway and a literature review, we look at the energy and climate impacts of existing and proposed datacenters, both quantitatively and in terms of stakeholder and public perceptions. The paper examines datacenter management and sustainability practices in the Nordic region. It explores what community impacts occur, and how communities manage conflicting objectives. It investigates the technical and policy options that can make datacenters more sustainable and/or lower-carbon and it explores associated stakeholder and public views in the three countries. In exploring these themes, our study examines the shifting energy governance of datacenters, including patterns of electricity consumption and cooling but also circular economy operations and power densities. We also analyze a series of 40 solutions for eco-friendly design or green datacenter management across the entire lifecycle. We conclude with implications for energy and climate policy as well as future research.

1. Introduction

Far from being in the “cloud”, our data is situated in specific locations for energy and climatic reasons. For instance, The North Atlantic – Finland, Sweden, Ireland and Iceland – has become a favorite location for Facebook, Google, and Amazon datacenters because the area promises access to inexpensive energy, Arctic temperatures to cool hot computers, stable governments, and tax incentives. The Arctic also represents the next frontier of energy services delivery, given its untapped energy resources [1]. Datacenters offer potential for economic diversification away from resource extraction: some Greenlanders, whose economy is currently reliant on mining, fishing and tourism, bolstered by a block grant from Denmark, are beginning to wonder if their country might function as a future datacenter hub, given its abundance of hydroelectricity, favorable tax conditions, and the availability of land.

Datacenters are nonetheless part of an extended sociotechnical system with an increasing environmental impact. Internet and online services account for about 10% of global electricity demand [2,3], and take

a similar proportion of electricity in most countries. The growth in energy powering the online services and data that society relies upon shows no sign of slowing, with about 20% annual growth in network traffic. Conservative models predict that online services and devices will rise to 20% of global electricity use over the next decade. The growth is currently unsustainable, unchecked, and represents a threat to energy security and the potential to lower carbon emissions.

The transformative potential of information and communication technologies (ICTs) on different sectors—and society in general—has been widely advocated [4], and they are often positioned as one potential means of reducing the energy-intensity of daily life [5]. However, the number of Internet-connected devices has now surpassed the number of people [6]. Studies with a focus on how Internet-connected devices are being used suggest that the general directionality of ICTs is unsustainable [7]. Estimates imply that Internet infrastructure (e.g. networks and data centers) is consuming more than the computers that they support [8]. In fact, Hirschier et al. [9] looking beyond the use phase of these devices, propose that data networks account for 90% of the total energy consumption for the entire lifecycle of tablets and smartphones.

The impact of Internet infrastructure is only due to worsen: forming

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List of abbreviations

CAGR	Compound Annual Growth Rate
CEO	circular economy operations
CRAC	computer room air conditioning
CRAH	computer room air handling
CUE	carbon usage effectiveness
DC SAR	datacenter sustainability assessment ranking
EDE	electronics disposal efficiency
EOC	Environmentally Opportunistic Computing
ERF	energy reuse factor
GB	gigabytes
GEC	green energy coefficient
IBA	Impact Benefit Agreement

ICT	information and communication technology
IT	information technology
PDU	power distribution unit
PDS	power distribution system
PSR	power system reliability/resilience
PSU	power supply unit
PUA	per unit area
PUE	power utilization/usage effectiveness
PWD	power density
R&D	research and development
SWGR	switchgear
UPS	uninterrupted power supply
WUE	water usage effectiveness
ZB	zettabytes

21% of global electricity by 2030 in the expected case, with an 8% or 51% share in the best and worst cases respectively [10]. Whilst efficiency improvements have been applied to information networks, the IEA have indicated such improvements are in a “battle” with data demand growth [11]. This continuing battle between use and efficiency is due not only to the aforementioned growth in the number of Internet-connected devices, but also the growth in Internet traffic as “households with higher speed connections are consuming significantly more data, especially those with superfast speeds” [12]. Global data traffic has a Compound Annual Growth Rate (CAGR) of 26% from 2017 to 2022, reaching an estimate of 4.8 zettabytes (ZB) per year by 2022 [13].

Such significant data growth pushes the need to expand networks to meet traffic requirements; this in turn enables more data-intensive devices or services in the computing industry and increases the associated demand for those technologies—leading to a vicious cycle of Internet demand and infrastructure growth [14]. Our use of ICTs is evolving unsustainably, and the expansion in the demand for Internet connectivity and data has been—in parts—built into new and evolving digital services. Industry players increasingly develop data-intensive layers (e. g. high-definition streaming, advertising, Cloud services etc.) to online services: many of which are hidden to end-users. These may be small changes by the technology industry that create fast, and significant impacts on the demand for data; for example, Facebook introducing video auto-play on its social media service led to a documented surge in traffic [15].

There is a temporal lock-in element to this, with the likelihood of cumulative impacts over time arising through ongoing adaptations to end-user Internet usage norms. Hence users are now streaming video as the default way to watch content, rather than more traditional (and arguably more sustainable) forms such as via broadcast television [16]; this is adding to the significant share of demand that video consumes (75% of global traffic in 2017). Despite these changes to digital devices and online services, there has been little societal consideration of or reflection on the environmental costs of the built-in growth, by either industry players, or the policies that support them. The UK’s Digital Strategy [17], as one example, highlights only the role of data networks in terms of the various investments it has made in infrastructure of this type. Of relevant, recent sectoral reports in the UK, perhaps only a recent report by Policy Connect considers the environment [18] and this is typically internationally rather than in a domestic context.

Both policymakers, and the technology industry, need to do more to combat the ever-growing demand for data and its associated energy impacts. If done, the energy savings could be considerable: as researchers have pointed out, “just” removing the video streams for YouTube content that end-users only listen to, could have a comparable reduction in emissions to running a datacenter on renewable energy [19]. Furthermore, future technology development trajectories (e.g. 5G,

connected cars) are only going to add to this issue of growing devices, services and data—therefore it is paramount we are better prepared for the environmental impact the computing sector will introduce going forward.

On average in Europe, we use our phones every 12 min and are spending on average 24 h a week online [20]. With such rates of economic growth, usage and benefits interwoven with the energy and environmental footprint of Internet demand, the climate implications merit policy attention [21]. With societies increasingly reliant on digital services, we are at a critical point where the sector is growing in social, economic, and political complexity, contributing to an array of externalities and benefits. Yet as the technical and social complexity of data services increasingly, their impacts become increasingly difficult to regulate effectively.

In this study, based on novel corporate data, expert interviews, focus groups, extensive site visits across Greenland, Iceland and Norway and a literature review, we look at the energy and climate impacts of existing and proposed datacenters. We ask: How are data centers managed with regards to concerns about energy consumption, climate change emissions, and sustainability? What do data centers construe as “low-carbon” or “renewable”? What best practices exist, and what worst practices ought to be avoided? We conclude with implications for energy and climate policy as well as future research.

2. Case selection and research design

We began by selecting the three Nordic countries of Greenland, Iceland and Norway to examine, given that the Nordic region is seen as an ideal location for datacenters given adequate land (much of it unused, or even given for free via government concession in Greenland); cold temperatures for natural cooling; clean sources of energy (such as hydroelectricity in Norway and Greenland, geothermal in Iceland); an attractive tax and investment climate with favorable industrial strategy; and notably good digital infrastructure and sound governance. Collectively, the three countries are home to 38 distinct datacenters shown in Table 1 and Fig. 1. All three countries are also part of the fiber optic superhighway with high-speed subsea cables shown in Fig. 2.

The foreword to the 2018 Ministry of Trade and Industry report – Datacentre Nation, sums up the drive for investment in Norway: Ministers from several Government departments highlight the attractive features of Norway for their establishment and operation, their employment and value creation benefits for the country, while the Minister of Local Government and Modernization calls for shorter processing time and increased predictability when processing plan proposals and applications to the public sector [22]. The report highlights that corporate tax has been reduced to 20%.

Compared with Norway, the deployment in Iceland has been somewhat slower. Iceland’s situation on top of a geological hotspot might be a

Table 1
List of datacenters and colocation centers in Norway, Iceland and Greenland.

Country	Data Center Name	Region
Norway	AQ Compute: NO-DC1	Oslo
	Availo DC0	
	Basefarm Oslo OSL3	
	Basefarm Oslo OSL5	
	Blix Gullhaugveien	
	Bulk: Oslo Internet Exchange (OS-IX)	
	DigiPlex Fetsund III	
	DigiPlex Hobel	
	DigiPlex Oslo Fetsund	
	DigiPlex Oslo Fetsund II	
	DigiPlex Oslo Rosenholm	
	DigiPlex Oslo Ulven	
	EVRY AS Gjøvik	
	Fujitsu Oslo	
	Green Mountain DC3-Oslo	
	IP-Only HMG9	
	Level 3 Oslo	
	SSC Forskningsparken Oslo	
	StoreSpeed Fredrikstad DC1	
	TaliaSonera Oslo	
	Verizon Oslo	
	Lefdal Underground Mine	Måløy
	Northern Data Lefdal	
	Arctic Circle Data Center Mo i Rana	Mo i Rana
	Avure Bergen	Kokstad
	Bulk Kristiansand N01	Vennesla
	Green Mountain DC1-Stavanger	Rennesøy
	Green Mountain DC2-Telemark	Rjukan
	Green Mountain Gismarvik	Gismarvik
	Troll Housing	Eide
Iceland	Advania Thor ICE-01	Reykjavik
	atNorth ICE02	
	Etix Fitjar #1	
	Opin Kerfi Korputorg	
	Verne Global	
Greenland	Vodafone Reykjavik	
	Etix Blönduós #1	Blönduós
	Tele Greenland Nuuk	Nuuk

reason for this. However, despite locationally-specific active geology, most of the country is nonetheless composed of stable basalt, with strong connectivity links via subsea cables and increasing activity in Bitcoin and other cryptocurrency mining.

Greenland was a (perhaps surprising) world leader and early adopter for dial-in internet in the 1990s, later moving towards high-speed fiber in 2008, and investing in a subsea cable connection to Canada (via Eastlink) and Iceland (via FarIce). The Arctic climate means that the average temperature does not often exceed 10° C even in the warmest months, and harsh weather creates an indispensable need for reliable electricity and heating, meaning it has an abundance of energy available for new datacenters [23].

With our three countries selected, we relied on five primary sources of original data for this study: corporate benchmarking information, semi-structured research interviews, focus groups, site visits, and a literature review. Our literature review materials were sourced from scholarly databases like Scopus, online sites like Google and government websites. We utilized these sources because [1]: research on datacenter (especially in the Arctic or Nordic region) is not yet mature [2], scholarly articles in standard sources like Scopus were fairly limited as a sole source of data and [3], of our need to understand the unique roles and perspectives of different governments towards incentivizing the data-center industry in their countries.

Firstly, we relied on *corporate benchmarking data* to identify particular communities or locations experiencing data center development, and also to identify the names of key firms that we could approach for our second method of data collection, the interviews. We also collected key electricity consumption, power resilience, power utilization effectiveness, cooling, and power density data.

In terms of data collection via *interviews*, we approached, largely by email, some 100 potential organizations and individuals considered to have a stake in datacenter development in Iceland and Norway. Our sampling strategy for the research interviews focused on:

- Datacenter managers and firms;
- Internet providers and telecommunications companies;
- Municipal authorities and planners;
- National ministries concerned with employment and economic growth;
- Environmental civil society groups;
- Energy companies and suppliers;
- Academic researchers studying the topic.

We completed 20 of these semi-structured interviews in English from March to May 2021 over Zoom video-call, made necessary by the Covid-19 pandemic, followed by selected in-person interviews in June and July 2021. We asked respondents the following, among other questions:

- Can you identify any case studies or examples of best practice, or worst practice, for datacenters in terms of (a) energy management and/or (b) sustainability?
- What community impacts arise, and how do communities manage conflicting objectives?
- What technical and policy options can make datacenters more sustainable and/or lower-carbon?

Interviews lasted between 30 min and 150 min, and were fully recorded and transcribed for anonymity, with interviewees giving informed consent. We refer to interviewees by country and number, i.e. NO1 for the first Norwegian interview, or G7 for the seventh Greenlandic interview.

To supplement our corporate and interview data, we also conducted six *focus groups* summarized in Table 2, with a combined number of 64 additional participants (8 per focus group). One group was one “urban” and one “rural” in each country, in terms of the residence of the participants, premised on the possibility of correspondingly different attitudes relating to employment opportunities. That is, urban areas offer a wider range of opportunities for employment than rural areas; to the extent that employment potential is a priority for participants, and to the extent that datacenters are perceived as offering such employment directly or indirectly, so urban-rural differences may be evident. The scripts for the focus groups began by probing awareness, knowledge and experience of datacenters; any associations; perceptions of the role of datacenters generally and in terms of connectivity to other countries; perceptions of sites and place-related impact; perceptions of their economic and employment value, their environmental impact and trade-offs among these and other factors. The Iceland script gave more time to exploring perceptions of cryptocurrency mining, elicited via a rather provocative video on the topic. All scripts included photographs, video and information conveyed orally for response elicitation purposes. Towards the end of the sessions, respondents were asked to rank, in order of importance to them, six issues associated with datacenters.

Fourthly, in terms of *site visits*, members of the research team visited Greenland, Iceland and Norway. As with the focus groups, a mix of urban and rural locations was chosen to maximize diversity. The site visits were conducted to both offer context and background and enable some site visits and in-person interviews. Fig. 3 depicts some of the specific locations visited.

Finally, we conducted a *literature review*. We searched both the academic literature on datacenter operations, performance, and development, as well as the policy and governance literature for specific details about policies, investment trends, energy systems, and other relevant information to help offer context and further triangulate our original data.

In the sections to follow, we present data from all five of our sources



Fig. 1. Map of datacenters and colocation centers across Norway, Iceland and Greenland. Source: Authors compilation of data from Greenland [100], Norway [101], Iceland [102].

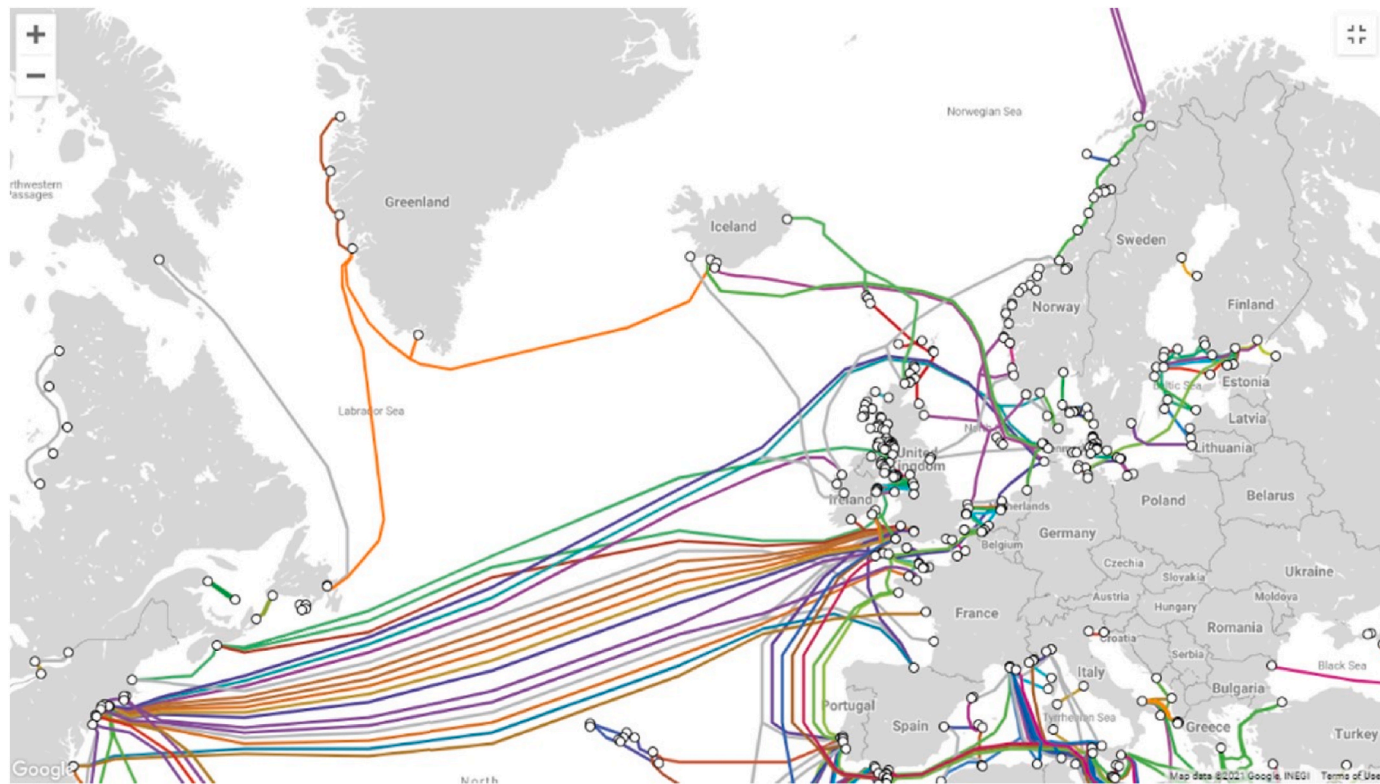


Fig. 2. Existing high speed digital cable infrastructure of the North Atlantic. Source [103]

Table 2

Summary of original focus groups conducted for this study.

Code name	Location	Number of participants
Iceland Group 1	Reykjavik	8
Iceland Group 2	Mixed rural participants	8
Norway Group 1	Oslo	8
Norway Group 2	Mixed rural participants	8
Greenland Group 1	Nuuk	8
Greenland Group 2	Sisimiut	8

when relevant and divide our results and discussion into three different themes. Section 3 discusses trends in digitalization and how they relate to datacenter development, energy consumption, and climate change. Section 4 showcases how datacenters are actually managed in within our Nordic countries. Section 5 presents results on techniques for more sustainable datacenter operation and management.

3. Digitalization and datacenter development in the context of energy and climate change

This section of the paper defines datacenters, and then discusses their energy requirements and environmental impacts, projection of their growth, as well as specific community acceptance issues arising in our three Nordic countries.

3.1. Defining datacenters and estimations of the industry

A datacenter refers to a group of computers or networked computers used by an organization to remotely store, process, or distribute large amounts of digital data. There are now over 8 million datacenters worldwide [24] and many more are still envisaged. According to Gartner, despite a 10.3% decline in datacenter spending in 2020, “end-user spending on global data center infrastructure is projected to reach \$200 billion in 2021, an increase of 6% from 2020” [25]. The ownership of

A. Kangerlussuaq, Greenland*B. Nuuk, Greenland**C. Sisimiut, Greenland**D. Reykjavik, Iceland**E. Oslo Norway*

Fig. 3. Research site visits conducted for this study across Greenland, Iceland and Norway.

these datacenters may assume one of the following models [26]:

- Enterprise/corporate: ownership of the facility, IT equipment and software systems is common. Typically used by governments and large technology companies like Apple, Amazon, Alibaba, Baidu, Facebook, Google, and Tencents.
- Co-location (wholesale and retail): ownership of the facility is separate from the one of IT equipment, software systems and their immediate accommodation. Thus, the ownership of the datacenter rents the infrastructure to allocate IT equipment. This ownership model is becoming prevalent as many public and private enterprises consider it to be cost-effective than building their own datacenters.
- Hosting (data carrier centers): ownership of the facility and the IT equipment is common, but the software systems are dedicated by others. Thus, the ownership rents both the infrastructure and the IT equipment to host information, servers, etc.

Many small-medium sized datacenters which were privately owned and operated by government agencies and private companies are either now being closed or consolidated into large scale facilities operated by Cloud service or datacenter colocation providers for reasons including cost-effectiveness, efficiency, disaster recovery, and business continuity [27–30]. The number of hyperscale datacenters —primarily for cloud and big data storage, as well as high powered computing — is expected to reach 628 in 2021, up from 541 in 2020 [31]. As of 2020, the U.S and China's share of hyperscale datacenters were 38% and 9%, respectively [32]. Also, the global colocation market valued at ~\$54 billion is dominated by 15 large colocation providers headquartered in the United States, China, and Japan which account for 50% of this value [33]. Developments in edge computing and a surge in demand for advanced infrastructure due to advent of 5G services are the major factors that are anticipated to drive the future growth of data center colocation market.

3.2. Energy and environmental impact of datacenters

The energy use requirements of datacenters are distinct from other industrial or commercial sectors, given the need for a high degree of resilience, as well as constant connectivity and service delivery. Information technology equipment such as servers and computers also have very specific thermal ranges, cooling needs, and requirements for specificity, leading to precisely controlled and maintained environments. This makes the energy demand for a datacenter 100 times higher per square meter than for normal office accommodations [34]. Datacenters also need to precisely control humidity, and take energy intensive avoidance measures, given that humidity can damage equipment, lead to water vapor, and even result in electrostatic discharges [35]. Fig. 4 illustrates a general schematic for energy supply from the main grid to a Tier 1 datacenter.

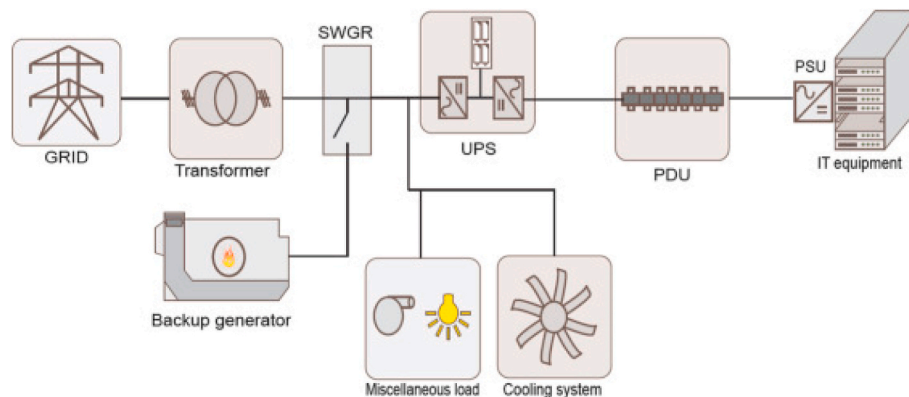


Fig. 4. Typical energy needs of a Tier 1 datacenter. Source [36]: SWGR = switchgear. UPS = uninterrupt power supply. PDU = power distribution unit. PSU = power supply unit. IT = information technology.

About half of total energy consumption for a typical datacenter is cooling, which consequently generates significant quantities of waste heat [37]. These needs can be exacerbated, and even oversized, if designers locate cooling and packed server racks too close together, or have poor air flow management, all of which can greatly increase energy needs. A focus on reliability rather than efficiency means most datacenters are also designed with “worst case scenarios” in mind, with all mechanical components oversized as a safety measure. This again leads to substantial amounts of wasted energy [38].

Datacenters vary in size from a single rack in a server closet to large server farms reaching 150,000 square meters [39]. Datacenter buildings tend to have three major spaces [40]:

- IT room: environmentally controlled and houses equipment and cabling that are directly related to compute and telecommunication systems which generate significant amount of heat. IT rooms are typically without windows to ensure air quality control, but this ramps up the energy required for cooling.
- Datacenter support area: houses power and cooling systems
- Ancillary services: offices, lobby, and restroom

As mentioned, the power supply to, and distribution within a datacenter are very important given the need for high operational reliability mandated by high quality of service requirements. There is no uniform power distribution system (PDS) design. The specificities of layout and operation requirements influence this. Generally, the emphasis is mainly on building adequate level of redundancies to ensure a desired quality of service [41]. A “Tier” system is used to indicate the level of redundancy (reliability) built into the IT and support system; system reliability increases with increasing tier levels [42].

Currently, the highest Tier is Tier IV. Tier IV datacenters have redundancies both in component and distribution path levels and are fault tolerant. The need for business continuity and resilience has also been touted as a motivation for Tier-IV datacenters [43]. Facebook, Apple, Microsoft, and Google are the major contributors to Tier IV data centers [44]. However, such increased redundancy results in large-sized equipment or multiple parallel operating equipment which increase the energy consumption of the datacenter.

Datacenter cooling systems are required to absorb the excessive amount of heat generated by IT equipment during their operation to avoid equipment failures and costly downtimes. Conventional cooling systems involve air cooling using computer room air conditioning (CRAC) or computer room air handling (CRAH) units and constant volume of air is supplied based on maximum design heat load [45]. As power densities increase, liquid cooling becomes more attractive but must be used cautiously due to the danger of leaks that could result in equipment damage [46]. Cooling systems have been reported to be the largest energy consumers in datacenters accounting for approximately

40–50% of datacenter energy consumption [47,48]. Inadequate localization of cooling, packed server rack layouts, and poor airflow management could ramp up cooling requirements and datacenter energy consumption.

Datacenter carbon footprints are often calculated by tracking the sum of carbon emissions from datacenter operations (called direct emissions), as well as both manufacturing or replacement of IT devices (including external storage and network switches), and the disposal or recycling of IT equipment (called embodied emissions). Fig. 5 presents an estimation of direct and embodied emissions for a “prototypical” datacenter in the United States, one with 20,000 vol servers, 40,000 external hard disk drives, 2060 network switches and an average power utilization effectiveness, or PUE [49]. The footprint is about 59ktCO_{2e} per year, but it also has considerable potential to decline with better lifecycle management and low-carbon electricity supply. Two key factors shape the carbon footprint and thus environmental performance of a datacenter: its electricity mix (particularly evident in Fig. 5), and whether one includes onsite emissions only (direct) or captures embodied emissions (indirect and offsite), although these embodied emissions represent “only a small contribution to the total footprint.” [50] One conclusion here is that embodied emissions are therefore smaller than direct emissions on an absolute basis, and thus the best path towards reducing emissions is through onsite operational efficiency.

Many of our expert interviewees spoke about issues of scaling, power supply, redundancy and export during our field research. IS5 said that:

I think that is one of the potential critiques that maybe I would have with the process, that question needs to be asked, if it's not already been - I think more consistently or more often - that we need to be really questioning: ‘OK, do we need this power and if we do, where will it be distributed to and how will it be used?’

NO3 discussed difficulties with the price of energy and cooling:

At the site we have 15 MW of power. [But] there are plenty more - hundreds of megawatts - in the power plant, which is just 300 yards from our site. So this is an extremely strategic location. We have like three to double [power] lines of support in. And we have a [diesel] generator. On top of that, we have doubled cooling. So if one of the fan [systems fail], we still have enough on the other one. So that's tier three ... doubled up everywhere and ... doubled the price ... it's not a cheap solution.

This again confirms the fairly unique energy profile of datacenters, placing greater emphasis on reliability and redundancy over energy efficiency or sustainability.

3.3. Projections of global datacenter energy use and growth

Although Masanet et al. write that “datacenters represent the information backbone of an increasingly digitalized world,” [52] they also consume prodigious amounts of energy in aggregate. Various

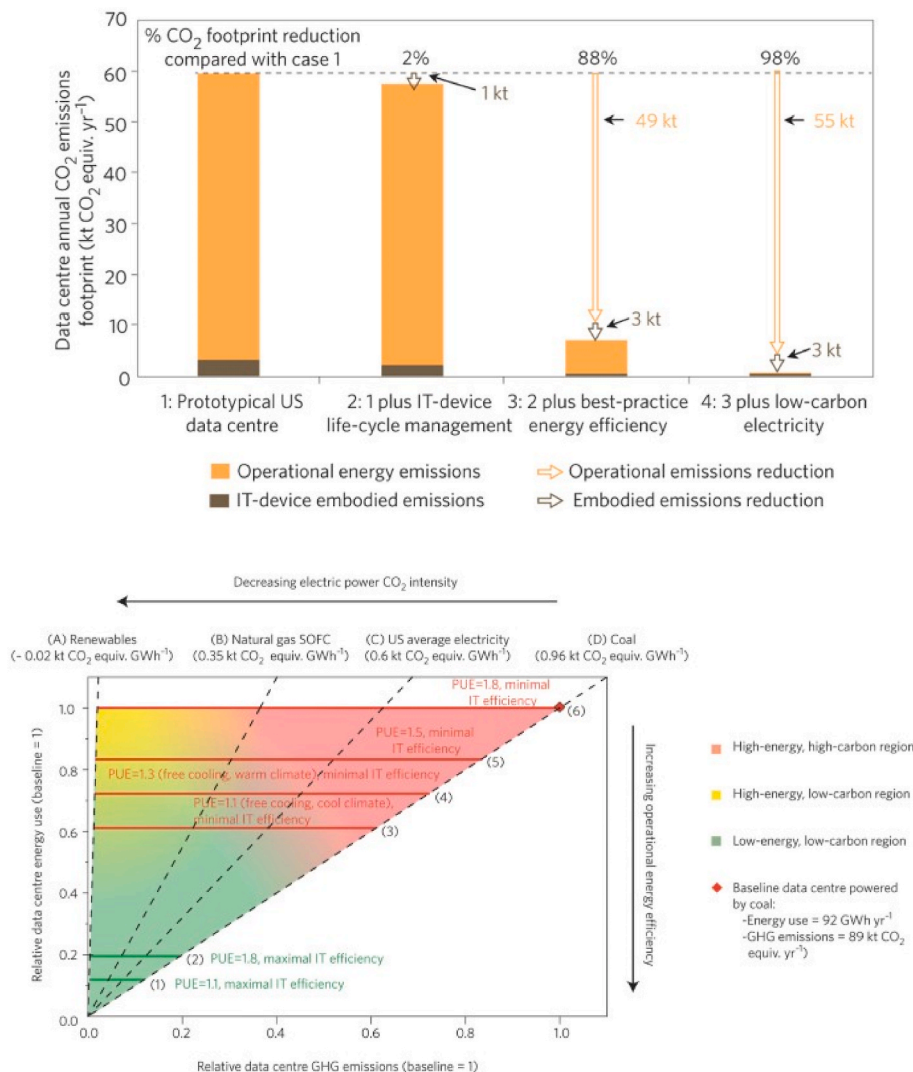


Fig. 5. Carbon footprints for typical datacenters in the United States

Source: [51] Note: In the top panel, the PUE is calculated by dividing a datacenter's total electricity use (kWh yr⁻¹) by the electricity used by the datacenter's IT devices (kWh yr⁻¹). Three cases illustrate plausible reductions in operational and embodied emissions (expressed by colored arrows). Life-cycle management adds IT-device lifetime extension and 100% recycling. Best-practice energy efficiency adds state-of-the-art IT-device and facilities energy management, with a PUE of 1.1. Low-carbon electricity adds average renewable power. In the bottom panel, the shaded area bounds the potential operational energy and carbon performance range of a prototype datacenter and illustrates the relative performance of different datacenter characteristics. Colored areas indicate general regions of energy-carbon performance.

interviewees (including NO1, NO4, IC2, G6 and G8) all spoke about how energy costs are the largest single expense for the datacenter industry, and that in some cases up to 90% of costs relate to energy supply (for electricity, heating, or cooling). Although datacenters are indeed getting more energy efficient (meaning each new one uses less energy), the sheer growth of the industry has offset efficiency gains. Masanet et al. calculate that global data center energy use rose to about 205 TWh in 2018 (approximately 1% of global electricity consumption), which is a 6% increase compared with 2010; whereas global data center compute instances increased by 550% over the same time [53]. This growth in total consumption is despite the energy intensity of the global datacenter industry decreasing by 20% annually since 2010. These estimations are presented in Fig. 6.

In comparative terms, datacenters can consume as much energy as entire cities, and datacenters not only consume energy, they also consume large amounts of water and also have large associated equivalent carbon emissions [55]. The number of server computers in datacenters has increased sixfold over the past decade to at least 30 million, and each server draws more electricity than earlier models as aggregate electricity use for servers also tends to double every five years [56]. Industry projections are that the world's data will grow from 33 zettabytes in 2017 to 175 ZB in 2025, and the amount of energy used by datacenters will continue to double every four years, meaning they have the fastest-growing carbon footprint of any area within the information technology and communications sector [57].

Indeed, the world's digital population is estimated to be growing exponentially at an annual rate of 9% [58]. Currently, over 50% of the world's population are internet users. The number of internet users worldwide increased from 1.1 billion in 2010 to about 4.7 billion in October 2020 (i.e., by about 330%). Of current users, 91.5% are unique mobile internet users, and by 2025, the number of global mobile internet users is expected to reach 5 billion, while IoT connections is expected to double from around 12 billion to 25 billion [59].

The increase in the dependency on digital ICT across all sectors of the modern global economy has led to an increase in the variety, volume, and velocity of data transmitted through digital devices over the internet (Fig. 7). According to the International Energy Agency, "global internet traffic surged by almost 40% between February and mid-April 2020, driven by growth in video streaming, video conferencing, online gaming, and social networking resulting in a 12-fold growth in global internet traffic" [60]. This growth in internet traffic can be significantly attributed to the COVID-19 pandemic as the internet and digital technologies have been used to retool society to survive the pandemic. This growth trend is expected to continue in 2021, as the world slowly defines the contours of the "next normal" in its battle with COVID-19 [61].

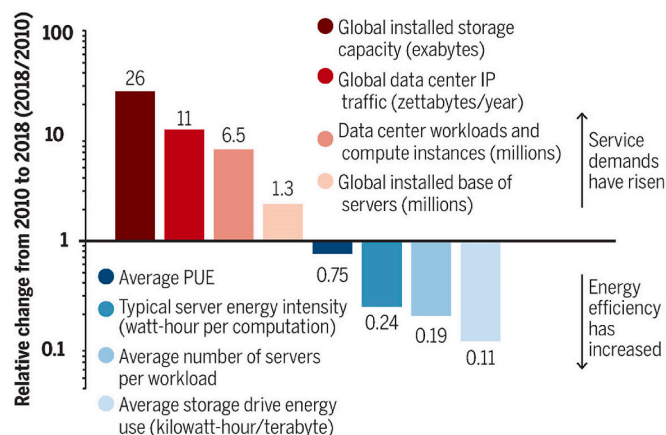


Fig. 6. Trends in global datacenter storage capacity, energy usage, and storage usage. Source [54] Note: PUE = power usage effectiveness. IP = internet protocol.

Daily data generation per capita is expected to reach 72 gigabytes (GB) in 2025 (from approximately 4 GB in 2018) [63]. Also, an International Data Corporation (IDC) study sponsored by Seagate indicates that "in 2025, each connected person will have at least one data interaction every 18 s. Many of these interactions are because of the billions of IoT devices connected across the globe" [64]. The exponential growth in data development is creating a significant need for the construction of more digital infrastructure, specifically datacenters which function as hubs and warehouses that aid the collection, storage, and transmission of data [65]. Improvements in technology, performance, and consumption patterns are difficult to predict, but several projections suggest that data center energy usage could surpass more than 10% of global electricity supply by 2030 [66].

Interestingly, we had conflicting perceptions in our focus groups and interviews regarding future growth projections across our three countries. Greenland Group 1 called Iceland and Norway "the future Mecca for datacenter development," but went onto to question "whether such similar development would ever come to Greenland." G6 even ruled datacenters development out for Greenland given the lack of both energy and subsea cable access:

For Greenland to see a big wave in future datacenter development, three big long-term investments are needed: a hydropower plant, a submarine cable, and building the datacenter. Datacenters can't project need for capacity or energy in 10 years' time, because of how fast things evolve, or the international superhighway of fiber cables are moving, hard for them to anticipate. A datacenter company would only invest if redundancy in infrastructure is sufficient for their needs, if energy is cheap, if future projections of growth are sound, and if politics is stable. You have none of these conditions in Greenland. A datacenter won't want to build their own power supply or grid, either, not even Apple, Google, or Facebook operates their own hydropower plants. Even though the government here grants concessions, and gives land away for free, even though datacenters would get huge discounts for energy, like fish processing plants, I still don't see it happening here. The bottom line is to work here, Greenland would need an extra power plant or two, with very cheap energy, and another submarine cable.

This informant's view may explain why Iceland and Norway host a multitude of datacenters of varying types and sizes, but Greenland currently has only one fairly small co-location center near Nuuk.

3.4. Community challenges and social acceptance

Moving from the technical to social and political realms of datacenters, our focus group data particularly identified some pressing community related concerns to datacenter development. Across all six of our focus groups, the participants had a basic awareness of the functions of datacenters, but had, for the most part thought little about datacenters per se. They associate them primarily with data storage for consumers and businesses and less so with high performance computing. A few gave "crypto" as a top-of-mind association. Several referred to "the cloud" and security of data storage was also referred to. Fiber-optic cable links and electric power supply were understood by some to be important preconditions for datacenter operations.

One community concern however was data privacy and how companies owning datacenters treat private information. One person in Iceland Group 1 stated that:

And so, these big companies like Facebook and so forth. They use these kinds of sectors to accumulate information, not only to accumulate them but also use whatever next step we take in life. And marketers in political science.

A man in Iceland Group 2 remarked that:

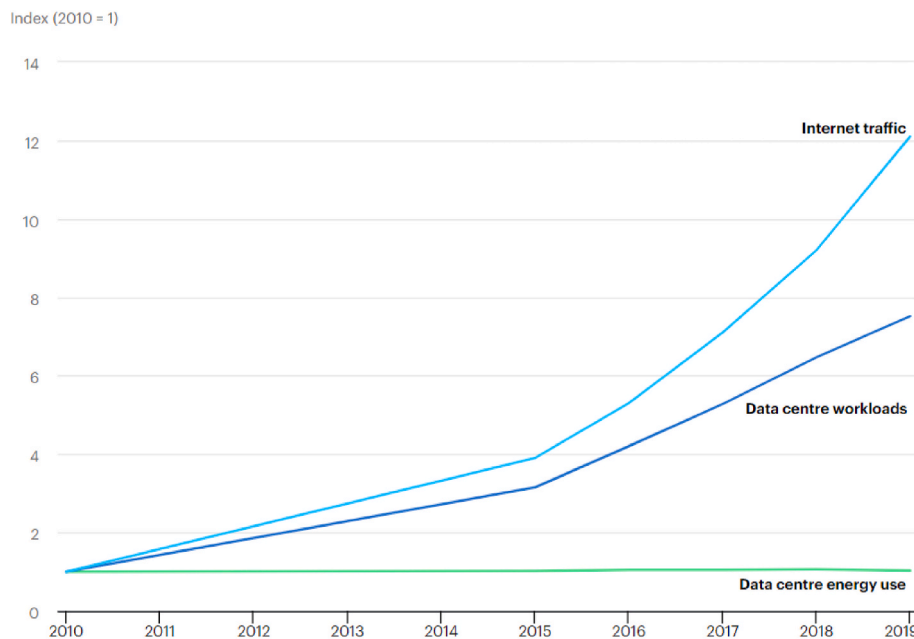


Fig. 7. Global trends in internet traffic, datacenter workloads and datacenter energy use, 2010–2019.

Source [62].

But yeah, it's driven by business not by the customer and most of the time, the computer, my Windows 10 or 11 - all these programs – add nothing, you know that? A lot or most of it is useless.

A woman in Iceland Group 2 added that:

If you are offered to store your data for free. That means you are a sales product like Facebook, because it's free. That means that information stored will be used by some touch to you and influence you.

And a young woman in Greenland Group 1 remarked that:

I don't trust datacenter companies to protect my interests or my data. They have more important priorities such as making money.

These comments all question the accumulation of private information, the utility of their business models, the use of information against people, and trust as barriers to datacenter legitimacy.

Cryptocurrency mining and Bitcoin production also arose as specific concerns. In terms of concerns and disbenefits, most participants in the Icelandic groups expressed moderate to strong disapproval of cryptocurrency mining, perceiving the energy consumption involved to be unjustified. This was replicated to a lesser extent in the Norwegian groups. It should be noted that the Icelandic groups were exposed to a rather provocative video on the topic, reflecting notable coverage of this in the international press. Several people in Icelandic groups wanted greater government control and regulation of what datacenters were doing, specifically in relation to cryptocurrency mining. For example, multiple participants in Iceland Group 1 said that "I would rather focus on a datacenter that is more ethically run ... to me bitcoins are not ethical, just waste... its computational power isn't being used to solve any problems" and "there's also a lot of questions because we don't know anything about them." Iceland Group 2 spoke such acts as a "mysterious, mysterious business" and Greenland Group 1 argued that "datacenters that use a lot of energy for the servers and for cooling, a lot of energy and a lot of heat, for cryptocurrency mining should be outlawed."

Other than cryptocurrency mining, there were two additional concerns. The first involved not the datacenters per se, but corporate users of citizen and consumer data – the uses and misuses to which this data may be put, including security failure via hacking. Participants generally

trusted datacenters themselves in terms of their own security efforts. The second main concern related to power consumption and consequent potential impacts on consumer electricity prices, perceived as including and consequent on the lower energy tax rates afforded to datacenters relative to aluminum plants, and the likely eventual need for construction of additional energy supply and distribution infrastructure. It should be noted that these concerns were not ubiquitous: some participants wanted more information about this issue of power supply and the impacts for consumer costs, i.e. themselves, including in relation to electricity tax discounts for datacenter operators relative to aluminum plants, before coming to a definite view.

While the latter ethic was notable and predominant, i.e. self-interest, albeit collective in terms of the country, participants accepted and approved of the carbon emissions benefits of locating datacenters in Nordic countries instead of warmer countries. This said, motives for this varied: while some held a universalist ethic [67], others were most concerned about climate warming effects close to home. Subsidiary concerns mentioned by individuals included: possible effects of sub-oceanic fiber-optic cables on marine mammals; issues of sufficiency and there being no end to development; in the Iceland group, concern about the lack of public debate about the future role of datacenters in Iceland and concern that this lack of debate might be deliberate.

In the next section, we examine the datacenter market in the Nordic region (primarily Norway and Iceland, and to an extent where possible Greenland) vis-à-vis the energy and environmental impacts of the industry, sustainability dilemmas, and management practices related to advances in deployments.

4. The shifting energy governance practices of datacenters in the Nordic region

To provide better context to datacenter operations, we examine and evaluate key factors/metrics for selected datacenters (12 for Norway and 6 for Iceland, evidence from Greenland where available) against established trends. This is necessary in benchmarking datacenters across the regions for further performance evaluations. Key selected metrics include power supply resilience, carbon footprint for power supply, PUE and contribution (benefit) to society (beyond job creation). Given Greenland has only a data colocation center, it has been excluded from

this section of the paper. Still, this comparison of 18 datacenters in the Nordic region enables us to examine best and worst practices, and also show how such datacenters are managed in the real.

4.1. Electricity sector-wide overview

Norway has the highest share of electricity produced from renewable sources in Europe, and the lowest emissions from the power sector. At the end of 2020, the total installed capacity of the Norwegian power supply system was 37,732 MW, and normal annual production was 153.2 TWh [68]. In 2020, Norway set a new electricity production record of 154.2 TWh [69]. This is about 10 TWh more than the average over the last 5 years. Good access to water in the reservoirs and increased wind power capacity were among the reasons for the record high production. Norway is now developing more renewable power production capacity than it has for decades. Wind power currently accounts for 10% of the production capacity and is now dominating investments.

About 85% of the total primary energy supply in Iceland is derived from domestically produced renewable energy sources [70]. This is the highest share of renewable energy in any national total energy budget. In 2016, geothermal energy provided about 65% of primary energy, the share of hydropower was 20%, and the share of fossil fuels (mainly oil products for the transport sector) was 15%. In 2013 Iceland also became a producer of wind energy. The main use of geothermal energy is for space heating, with the heat being distributed to buildings through extensive district-heating systems. About 85% of all houses in Iceland are heated with geothermal energy.

In 2015, the total electricity consumption in Iceland was 18.8 TWh. Renewable energy provided almost 100% of electricity production, with about 73% coming from hydropower and 27% from geothermal power. Most of the hydropower plants are owned by Landsvirkjun (the National Power Company) which is the main supplier of electricity in Iceland. Iceland is the world's largest green energy producer per capita and largest electricity producer per capita, with approximately 55,000 kWh per person per year. In comparison, the EU average is less than 6000 kWh [71].

In Greenland, a prospective frontier for datacenter development, almost three quarters of electricity supply from the national energy company Nukissiorfiit is low-carbon (mostly from hydroelectricity with some solar, wind, and waste to energy). However, the national energy mix involves many independent and isolated suppliers that tilt the overall energy balance to fossil fuels [72]. Collective electricity and heat are provided by many utility companies and off-grid providers, some through diesel plants, others through oil-based boilers along with district heating networks in some of the larger cities. Fig. 8 however shows that only two existing plants (in green) could expand capacity, the others are either at capacity (yellow) or at risk of being above capacity (red: demand exceeds supply).

4.2. Datacenter power supply and resilience plans

Our corporate benchmarking data from 12 datacenters across Norway evidences a 100% connection to the Norwegian grid. To further boost resilience of power supply to datacenters, operators have in some cases adopted multiple feed-ins from various external power generation/transmission units as well as deploying local solutions ranging from diesel backup generators and UPS solutions.

NO2 explained both the need for reliability, and their particular approach to it, as follows:

Yes there is a business ecosystem developing around and that system is mainly within the area of electricians and automation engineers. [Also] those mechanical companies doing piping, cooling and so on, [who] were running generators and we need knowledge and experience within that. And the thing with the datacenter is that the

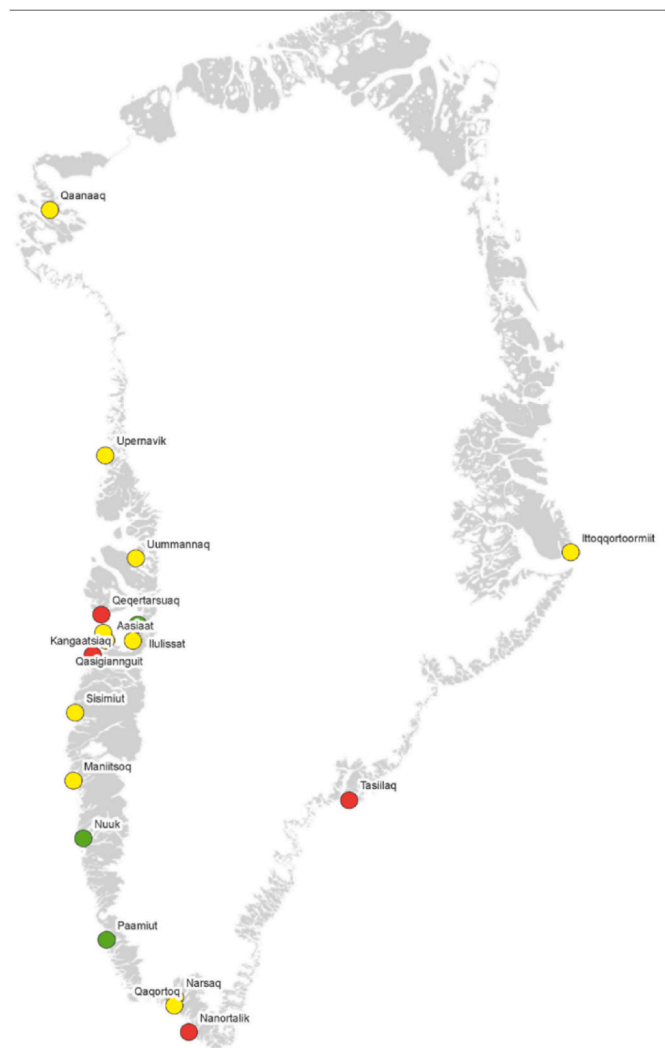


Fig. 8. Current capacities of electricity and heat supply plants in relation to demand in Greenland, 2018. Source [73].

workload operated in a datacenter is at the criticality level that the amount of maintenance done in datacenter is far above what you normally do if you have a factory or anything else. We have to be sure that the datacenter is up running 24-7; we cannot accept any failure, so the level of maintenance is high and the level of testing is high.

As shown in Fig. 9, 100% of the surveyed datacenters have grid supply with 83% having a configuration of either UPS/battery or diesel generators or both. A major observation is the absence of any onsite displacement of electricity. Similarly, the 6 datacenters we examined across Iceland evidences a 100% connection to the grid similar to Norway. As also shown in Figs. 9 and 100% of the surveyed facilities have grid supply with 33% having a configuration of either UPS/battery or diesel generators or both. Similar to Norway, the absence of any onsite displacement of electricity is observed.

4.3. Power resilience benchmarking

Table 3 presents to what extent each surveyed datacenters can remain operational in the event of a major fault from its power supply. Not all datacenters can survive N-1 faults with 42% surviving N-2 faults and no surveyed facility surviving N-3 faults. By N-1 faults, we mean outages caused by a single equipment breakdown in primary power supply while by N-2 faults we mean outages caused by a single

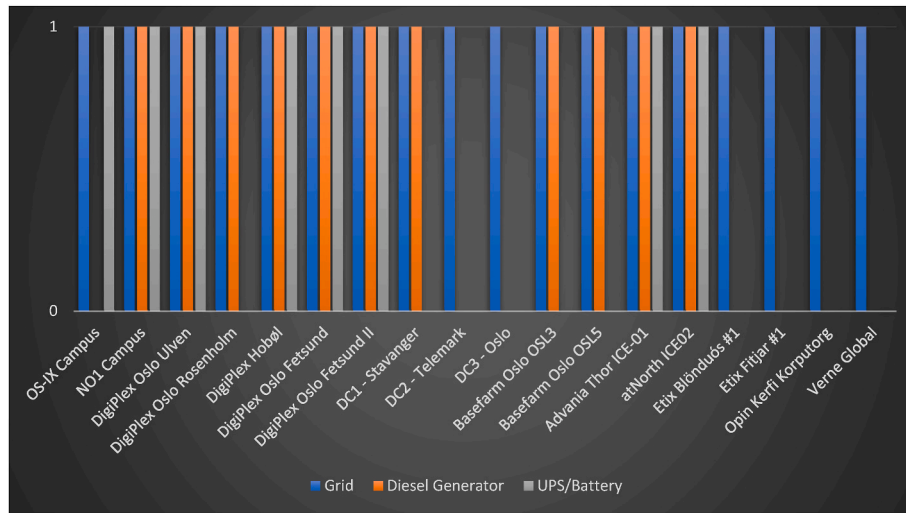


Fig. 9. Power mix for selected datacenters in Iceland & Norway.

Table 3

Power resilience benchmarking for selected datacenters up to N-3.

Country	DC	N-1 fault	N-2 fault	N-3 fault
Norway	OS-IX Campus	V	X	X
	NO1 Campus	V	V	X
	DigiPlex Oslo Ulven	V	V	X
	DigiPlex Oslo Rosenholm	V	X	X
	DigiPlex Oslo Hobøl	V	V	X
	DigiPlex Oslo Fetsund	V	V	X
	DigiPlex Oslo Fetsund II	V	V	X
	DC1 - Stavanger	V	X	X
	DC2 - Telemark	X	X	X
	DC3 - Oslo	X	X	X
	Basefarm Oslo OSL3	V	X	X
	Basefarm Oslo OSL5	V	X	X
Iceland	Advania Thor ICE-01	V	V	X
	atNorth ICE02	V	V	X
	Etix Blönduós #1	X	X	X
	Etix Fitjar #1	X	X	X
	Opin Kerfi Korputorg	X	X	X
	Verne Global	X	X	X

^V Implies datacenter still operational;

^X Implies datacenter not operational.

equipment breakdown of a first backup source. By N-3 faults we mean outages caused by a single equipment breakdown of a second backup source. The red colored cells represent datacenters that would not be operational during faults. In all datacenters surveyed, duration of operation for backup systems has not been considered. A critical finding from Table 3 is the large number of datacenter operators who do not feel the need for multiple backup systems in the event of multiple power supply failures.

4.4. Power utilization effectiveness (PUE) benchmarking

Most studies assessing the performance of datacenters focus on energy efficiency as indicated by single-issue datacenter performance metrics such as PUE, carbon usage effectiveness (CUE), water usage effectiveness (WUE), energy reuse factor (ERF), Green energy coefficient (GEC), and more recently, electronics disposal efficiency (EDE) [74,75]. Of these, the PUE is the most used metric. It is primarily an energy efficiency measure that assesses the ratio of a datacenter's total energy consumption to its IT load. It drives the need to minimize the power usage of non-IT equipment and processes within a datacenter [76]. Thus, a PUE of 1 is considered ideal. Fig. 10 presents the PUE values of the 12 datacenters surveyed.

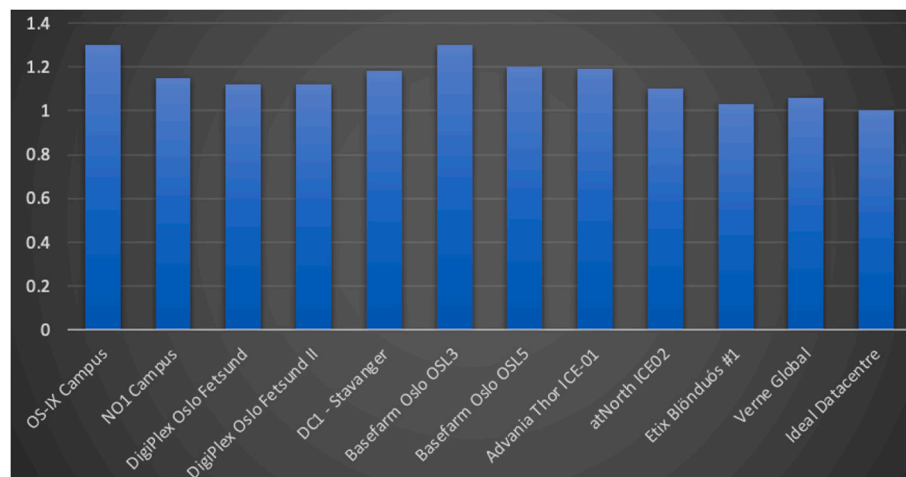


Fig. 10. Power usage effectiveness for select datacenters in Iceland & Norway. Note: the ideal PUE value is 1.0.

4.5. Datacenter cooling, power densities and heat reclamation

As seen in Table 4, cooling strategies range from air-to-air cooling to chilled water system etc. In both Iceland and Norway, the predominant cooling strategy is the direct free air method. Furthermore, we examined to what extent datacenter operations reuse waste heat generated either for local consumption or community district heating during winter months. As our data indicates, heat reclamation is also rarely used/not documented. In Norway, only 3 datacenters of the 12 surveyed have documented heat reclamation or heat export capabilities, and in Iceland, none of them has any documented evidence of such heat reclamation. As also shown in Table 4, power densities vary in Norway from 0.0008 MW/m² for Basefarm Oslo OSL5 to 0.0020 MW/m² for Basefarm Oslo OSL3, and in Iceland from 0.0011 MW/m² for Verne Global to 0.0080 MW/m² for Etix Fitjar #1.

G4 also spoke about the use of natural cooling for datacenters in Greenland, and the attractiveness of the Arctic environment in general, stating that:

Cooling connects to both economy and also the environmental impact of a datacenter, it creates a lot of heat, but here you can literally just open the doors (laughs) and cool it off. Here in Greenland, we took charge of a new datacenter over the winter, and due to bad weather in deliveries we had to operate without a main cooling facility. Our solution was to literally run on natural air, without backup, when it got too warm, we simply opened the doors and posted a guard. So our cooling system consisted of a guard and a fan. We would do it more but most of our facilities are too small. The reuse of heat from a datacenter if its split will be easily reused in Greenland. Other benefits are our location, right between North America and Europe, and very favorable taxes and even free concessions for land, many things in place to make this a possibility.

G7 added that the reuse of residual heat was not as easy as it sounds. As they said:

The datacenters in Denmark and Norway, some of them are using residual heating, but that can be difficult. It requires you to either

build a datacenter close to hydropower or geothermal energy with short transmission line, but then you are too far away from city to take the heat; or you put them here in a city, then you have a longer transmission line, high costs, and transmission losses of 10–12% on power. It's a dilemma.

4.6. Comprehensive sustainability assessment of Nordic datacenters

How do multiple datacenters perform on various sustainability metrics? To assess more synthetically and comprehensively the performance of datacenters across Norway and Iceland, the final part of this section conducts a sustainability assessment. We utilize 4 indices – PSR, PUE, power density (PWD) and per unit area (PUA). PUA is computed as average datacenter space benchmarked against 10,000 m². Values for each are averaged and compared.

Table 5 presents the overall ranking/assessment of the datacenters surveyed in Norway and Iceland. For each key area, 3 values A, B and C are used with A being the highest, B for mid-level and C for below mid-level assessments. To rank PSR, datacenters that can remain operational during N-2 faults are ranked A, datacenters that can remain operational during N-1 faults only are ranked B while datacenters that will trip off during N-1 faults are ranked C. In ranking PUE, we adopt a tier approach. Mathematically, $1 \leq PUE < 1.16$ is ranked A; $1.16 \leq PUE \leq 1.19$ is ranked B while $PUE > 1.19$ is ranked C. In ranking PWD, datacenters exporting waste heat to community for district heating are ranked A while those utilizing waste heat for local use or have in place waste heat reclamation systems are ranked B. All other datacenters are ranked C.

Fig. 11 presents the radar plot showing the comparison between datacenters in Norway and Iceland. This comprehensive and comparative assessment reveals some striking findings. The average PSR value for Norway and Iceland was 1.75 and 2.33 respectively. This implies that datacenters in Iceland are 33% less resilient than those in Norway. Norway datacenters incorporate more power redundancy in their design compared to Iceland. With up to 42% of datacenters in Norway capable of surviving a N-2 power outage compared to 33% of datacenters in

Table 4
Datacenter area, power, cooling technology, heat reclamation/export and computed power densities.

Facility	Area (m ²)	Power (MW)	Cooling technology	Heat export/reclamation	Power densities (MWm ⁻²)
OS-IX Campus	10000	14.4	N+1 cooling	None documented	0.0014
NO1 Campus	1400	>2.4	Latest adiabatic indirect cooling system technology	None documented	0.0017
DigiPlex Oslo Ulven	5100	6.8	Chilled water system with mechanical cooling system (2 N cooling available) with modern compressors (free cooling capabilities)	Heat export to district heating as part of its CSR	0.0013
DigiPlex Oslo Rosenholm	2200	3.2	Dual coil DX compressors, free cooling and external adiabatic dry coolers	Waste heat is used to cool campus during the winter months	0.0015
DigiPlex Hobøl	3200	6	Air-to-Air indirect evaporative coolers with rainwater reuse for cooling systems	Waste heat reclamation	0.0019
DigiPlex Oslo Fetsund	4200	8.4	Air-to-Air indirect evaporative coolers	None documented	0.0020
DigiPlex Oslo Fetsund II	2200	3	Self-contained Air-to-Air cooling plant with N+1 redundant Air-to-Air indirect evaporative coolers	None documented	0.0014
DC1 - Stavanger	22600	26	Titanium heat exchanger and cold water from a nearby fjord.	None documented	0.0012
DC2 - Telemark	40000	35	2 N cooling with Uniflair Chillers	None documented	0.0009
DC3 - Oslo	75000	75	Innovative cooling technology utilizing wet and cool climate achieving 25–30% efficiency improvements	None documented	0.0010
Basefarm Oslo OSL3	1300	4	N/A	None documented	0.0031
Basefarm Oslo OSL5	6000	5	Highly efficient indirect air-to-air cooling	None documented	0.0008
Advania Thor ICE-01	2700	3.2	Indirect adiabatic and direct free air	None documented	0.0012
atNorth ICE02	13750	80	Direct free air	None documented	0.0058
Etix Blönduós #1	12500	39	Direct free air	None documented	0.0031
Etix Fitjar #1	1000	8	Direct free air	None documented	0.0080
Opin Kerfi Korputorg	5000		N/A	N/A	
Verne Global	20903	24	Indirect free air cooling	None documented	0.0011

Table 5

Datcenter sustainability assessment and ranking for the selected datacenters surveyed in Norway & Iceland.

Datcenter	PSR	PUE	CEO PWD	DC SAR
OS-IX Campus	B	C	C	BCC*
NO1 Campus	A	A	C	AAC*
DigiPlex Oslo Ulven	A	C	A	ACA^
DigiPlex Oslo Rosenholm	B	C	B	BCB^
DigiPlex Hobøl	A	C	B	ACB^
DigiPlex Oslo Fetsund	A	A	C	AAC*
DigiPlex Oslo Fetsund II	A	A	C	AAC*
DC1 - Stavanger	B	B	C	BBC*
DC2 - Telemark	C	C	C	CCC*^
DC3 - Oslo	C	C	C	CCC*^
Basefarm Oslo OSL3	B	C	C	BCC*
Basefarm Oslo OSL5	B	C	C	BCC*
Advania Thor ICE-01	A	B	C	ABC*
atNorth ICE02	A	A	C	AAC*
Etix Blönduós #1	C	A	C	CAC*
Etix Fitjar #1	C	C	C	CCC*^
Opin Kerfi Korputorg	C	C	C	CCC*^
Verne Global	C	A	C	CAC*

Note: PSR = power system reliability. PUE = power utilization effectiveness. CEO = circular economy operations. DC SAR = datacenter sustainability assessment ranking.

*CEO value as been assumed as C since no documented work provides for this.

^PUE value of C has been assumed since no documented work provides for this.

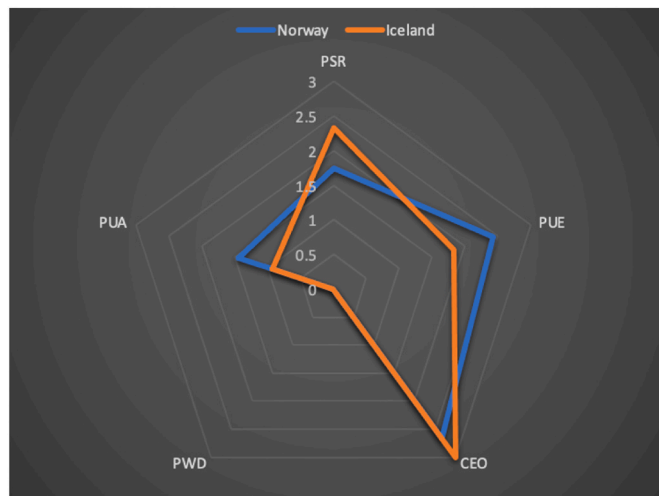


Fig. 11. Radar plot cross-parameter comparison between datacenters in Norway and Iceland. Note: PSR = power system reliability. PUE = power utilization effectiveness. CEO = circular economy operations. PUA = per unit area. PWD = power density.

Iceland, Norway does offer better resilience in the event of major disruptions. A lower PUE (ranged) value for Iceland (1.83) exists compared to Norway (2.42). This implies that datacenters in Iceland have lower power electricity demand for other needs beyond the datacenter. With regards to cross-community integration, Norway-based datacenters with a CEO value of 2.67 can in some instances feed into the district heating network or displace local heating demand (within the campus) during winter months. This is far better than datacenters in Iceland with a computed CEO value of 3 and no documented evidence of existing community integration. Datacenters in Norway can thus interact with their host community through central district heating systems thus offering more resilience to the overall energy network. Datacenters in Norway utilize 50% less electricity per unit area compared to those in Iceland. Also, datacenters in Norway are more than 50% bigger than those in Iceland. When viewed with PWD and PUE values, it is safe to conclude that datacenters in Norway are more efficient in power usage

when compared with those in Iceland.

5. Solutions for more sustainable datacenter performance and policy implications

This great variation in performance across Nordic datacenters does strongly suggest that scope for improvement exists. As one report noted, given these sustainability challenges, “the creation of green, sustainable, multi-tenant data centers has become essential in both an environmental and a business sense.” [77] NO2 also noted that:

You have datacenters today that were built early 1990s and they’re more than 30 years old and they’re still operational. You probably have to do some modernization and you’ll see that they are not that energy efficient as new ones today. You see, the trend of the kilowatt [consumption] per rack is increasing, so you probably don’t have the capacities in that old datacenter, but you can still use quite a lot of that infrastructure and just modernize parts of it or by adding on more cooling and power, meaning that the electrical and mechanical infrastructure could live for decades. We’ve said in our calculation a minimum of 25 years, but we see they could easily live longer, or they could work in cooperation with a modernized infrastructure. We still utilize some of those through some of the infrastructure that was built from day one. But obviously there is room for improvement.

One study concurred and noted that “old mainframe computers are bulky power hogs that demand a lot of cooling.” [78].

There is admittedly transformative potential to improve the energy efficiency and sustainability of datacenters, a trend already proven in part by history. For example, one assessment looking at the electricity intensity of data transmission (core and fixed-line access networks) concluded that it has decreased by half approximately every two years since 2000 [79]. But innovation can only carry the industry so far, and further improvements in energy efficiency alone will be unable to keep up with the sheer growth in datacenter usage and the need to further decouple electricity demand from our ever-increasing appetite for digitalization and data services [80].

Indeed, many suggest that the digitalization industry needs to move towards “green data centers” that are “built on pillars of commitments to innovative green and renewable strategies – including green power, water reclamation, zero water cooling systems, recycling and waste management, and more. They do not contain obsolete systems (such as inactive or underused servers), and take advantage of newer, more efficient technologies.” [81].

With the aim of achieving this goal, this section of the paper discusses seven core scales or themes across the whole system or entire lifecycle of a datacenter, from design and construction of energy use and cooling to waste and government policy (see Fig. 12). As Fig. 12 illustrates, our holistic suggestions cover both direct and onsite emissions as well as indirect and embodied emissions. The figure also depicts how strong policy and governance can shape multiple elements of the system, acting as levers that shape future development. Drawn from a mix of available evidence, especially [82,83], as well as our original data, we present a holistic array of 40 specific options across these seven themes to make datacenters more sustainable solutions summarized by Table 6. We now discuss these solutions in greater detail.

Source: Authors.

5.1. Advances in datacenter design and construction

Our first suite of recommendations center on better design and construction of datacenters themselves. This can include “green design” principles such as energy efficient and environmentally sound components, computers, servers, and cooling equipment, or “green manufacturing” techniques such as electronic components, computers,

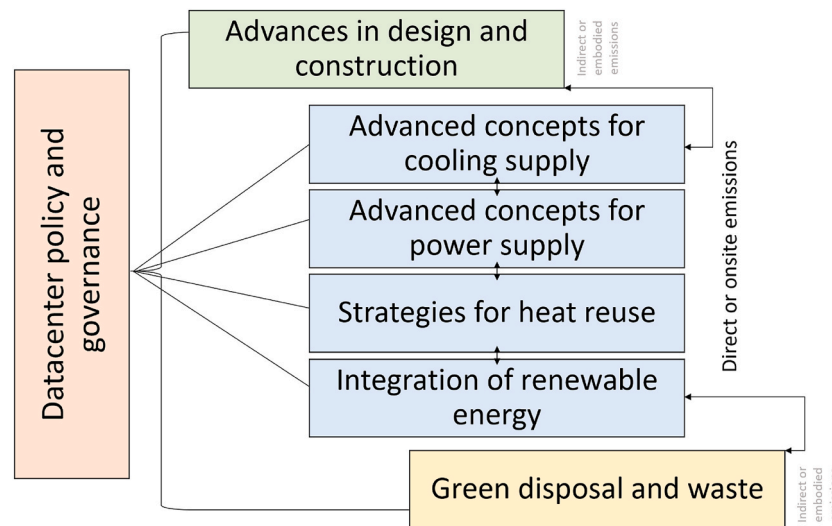


Fig. 12. A whole systems approach to datacenter sustainability.

and other associated subsystems with minimal or no impact on the environment [84]. The most “eco-friendly” datacenters on the market today can be designed to have a synthetic white rubber roof, white paint to enhance albedo, and carpet with low counts of volatile organic compounds. Countertops and server racks can be made from recycled products, and mechanical and electrical systems can be set to optimal efficiency. Natural light can be used along with energy-efficient windows, skylights, and sky-tubes. A nonprofit group the “Green Grid” even publishes white papers on how to propagate the best energy-efficiency practices in datacenter design and construction.

Green metrics, assessment tools, and methodology can also be used to improve data center layout and location, power management, and energy-efficient computing. Environment-related risk mitigation measures can also ensure datacenters are optimized to consume minimal amounts of energy, recycle excess amounts of heat, consume minimal water, and have other minimal effects on the natural environment.

Virtualization is another key strategy to reduce resource use at datacenters. Virtualization enables one physical server to host multiple virtual servers, enabling datacenters to reduce infrastructure needs by using a smaller number of more powerful servers with less electricity needs. This can ensure better hardware usage but also reduce datacenter floor space, reduce energy demand, and make better use of computing power. Virtualization can also assist with a technique known as consolidation. One problem with datacenter design is that it is hard to predict hot spots or uneven computer temperatures which will vary by the season, tasks undertaken, air circulation, and the power profile of a given task. Consolidation optimizes the maximum number of virtual machines with the minimum number of physical hosts, while also turning off idle hosts. It can improve power efficiency by up to 30%, reduce cooling needs by 15%, and see inlet temperature distribution between 2 °C and 5 °C lower than other approaches [85].

A final technique is to build larger datacenters that have better economies of scale and can synergize sustainability benefits in their design and operation. Masanet et al. argue that the largest decrease in the energy use of data center cooling and power provisioning relate to shifts away from smaller traditional datacenters towards larger and more energy-efficient cloud and hyperscale datacenters [86]. These larger facilities have much lower reported PUE values along with more advanced cooling systems and power efficiencies. Policy implications to facilitate suggested measures will center around enabling initiatives and grants from government and associated regulatory bodies specifying material pools as well as expected limits for energy usage for non-IT requirements.

5.2. Advanced concepts for cooling supply

Our second basket of solutions all center on cooling, including a variety of technical options ranging from free cooling or natural cooling to hydrogen fuel cells, to hot and cold aisle containment, increasing allowable IT temperatures, and better cooling management. Other options here include variable air flow, running datacenters at partial load, and investing in both high energy-efficiency components or thermal energy storage. Free cooling has been shown to reduce the PUE by cooling equipment with natural or outside air, directly routed into the datacenter when the weather permits. Solid oxide fuel cells also hold promise for lowering data center PUEs and providing facility cooling [87]. Considering that the cooling method adopted will to a large extent be dependent on location, available resources (cold water from fjords for example) and cost, national governments can facilitate the use of tax incentives including R&D grants and minimum heating requirements per unit area to incentivize businesses to adopt advanced technologies in meeting their heating needs (a theme we return to in Section 5.7).

5.3. Advanced concepts for power supply

Our third collection of solutions relate to electricity and power supply, not surprising given that this is perhaps the best known and most discussed aspect of datacenter management within the industry. For example, one survey of 1500 respondents across 758 organizations in Australia and New Zealand noted that “reducing power consumption” was the single most important operational factor perceived by data-center managers there (see Fig. 13), even ahead of “reducing costs.”

Lowering electricity use onsite can be accomplished through a variety of techniques, including the advanced use of energy storage devices, reliance on direct current installation, bypassing UPS in normal operating conditions for improved energy efficiency, or modulating UPS for enhanced efficiency. Encouraging and incentivizing rapid reductions in PUE such as better air flow management or temperature set point optimization can also accomplish significant energy savings [89]. It must however be highlighted that reducing power consumption must not compromise datacenter performance and reliability. To limit burdening the existing grid with supporting datacenter redundancy plans, policy makers can disincentivize extra power consumption from the grid during periods of constraint by charging excessive rates to datacenters as well as associated emissions tariffs for onsite generators utilizing fossil fuels. This way datacenter operators can redirect efforts towards using advanced onsite storage technologies that place minimum or no demand on the existing grid and can even earn them renewable

Table 6

Summary of 40 specific solutions or advancements to make datacenters more sustainable.

Scale of the system or lifecycle	Solution
Advances in datacenter design and construction	1. Green or eco-friendly design 2. Green manufacturing 3. Green metrics, assessment tools, and methodology 4. Environment-related risk mitigation 5. Virtualization and consolidation 6. Centralization and economies of scale via cloud computing or hyperscale facilities
Advanced concepts for cooling supply	7. Free cooling strategies 8. Fuel cells 9. Hot and cold aisle containment 10. Increasing allowable IT temperatures 11. Cooling management 12. Variable air flow 13. Partial load 14. High energy efficiency components 15. Thermal energy storage integration
Advanced concepts for power supply	16. Advanced use of energy storage devices 17. Direct current installation 18. Bypass UPS in normal operating conditions for improved energy efficiency 19. Modular UPS for enhanced efficiency 20. PUE enhancements
Strategies for heat reuse	21. Utilization of waste heat and heat recovery 22. Liquid cooling 23. Environmentally Opportunistic Computing 24. District heating 25. Absorption refrigeration
Integration of renewable energy	26. Onsite generation from onsite renewables 27. Onsite generation from offsite renewables 28. Offsite generation 29. Renewable energy supply from third parties
Green disposal and waste	30. Responsible disposal and recycling 31. Ecolabeling of IT products
Datacenter policy and governance	32. Energy efficiency standards for equipment 33. Tax credits and procurement standards 34. Public funding for R&D 35. Regulatory compliance 36. Impact Benefit Agreements 37. Equitable taxation schemes 38. Restrictions on cryptocurrency mining 39. Require local content or employment 40. Ensuring transparent and reliable data

Source: Authors. Note: IT = information technology. UPS = uninterrupted power supply. PUE = power utilization efficiency. R&D = research and development.

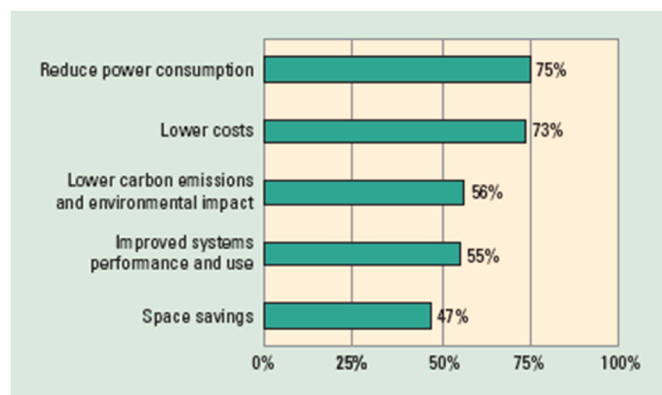


Fig. 13. Stated preferences for datacenter solutions in Australia and New ZealandSource [88].

energy credits.

5.4. Strategies for heat reuse

Better heat reuse and the utilization of waste heat is our fourth collection of solutions, and this can include liquid cooling, heat recovery, Environmentally Opportunistic Computing, district heating, and absorption refrigeration. These can even be integrated with demand response to further enhance system energy efficiency [90].

For instance, liquid cooling is several hundred times more energy efficient for cooling hot servers than air. Heat and hot water used in datacenters have already been utilized to provide district heating to neighborhoods nearby, and liquid cooling systems can increase both the working temperatures the IT room and equipment allowing the use of free cooling. When properly optimized, this can even eliminate the need for chillers and it facilitates thermal energy for reuse in cold climates for desalination, for greenhouses, for absorption cooling, or even for hot tubs and swimming pools [91]. Our focus groups indicated public support for such measures and some awareness of the options – for example, a participant in Greenland Group 1 noted that: “I know in Denmark, they use waste heat from their datacenters to power homes, so we actually need the heat, recirculate it across the town, and cleverly ensure nothing is wasted.” Stakeholder G9 also spoke about “best practice” options for heat recycling in Greenland, given that they already have district heat networks powered by a mix of fish waste, solid waste incineration, wind power, and solar power (See Fig. 14). As G9 said, “a datacenter could easily fit into this network and help circulate and recirculate heat.”

Waste heat recycling was also a popular theme in the other focus groups. When time allowed, the groups were shown a video of waste heat reuse from a Swedish datacenter, the heat being added to the town’s district heating system, which is fueled principally by local forestry. The discussion sequence from Iceland Group 2 was positive but also skeptical:

“Seems really positive.”

“It does indeed seem very positive. So I’m just wondering where the catch is.”

“They’re not giving the excess energy away, that’s for sure ...”

“It also looks like they’re trying to associate themselves with clean energy.”

“I don’t trust it too good to be true.”

Norway Group 2 were wholeheartedly positive:

“It was more impressive than the other commercial you showed us”.
<the Kolos video>

“More informative. In that one we had to guess what they were saying, but in this one they actually said it in words.”

<So you’re all positive about this type of waste heat reuse?>

“Yes”

“Of course”.

“It made sense. They managed to sell the idea. I’m sorry to say it, the Swedes did it much better than the Norwegians.

“Don’t tell them!”

Another noteworthy solution is known as “Environmentally Opportunistic Computing”, or EOC. EOC envisions a datacenter as a series of distributed heat suppliers for other buildings, distributing computational loads across a number of distinct nodes based on where heat is needed. In pilot studies, absorption refrigeration and heat reuse through an Organic Rankin Cycle were found to be the most promising and

A. Sisimiut Waste Incineration Plant



B. Royal Greenland fish processing waste facility



C. Wind power on the Sisimiut grid



D. District heating networks

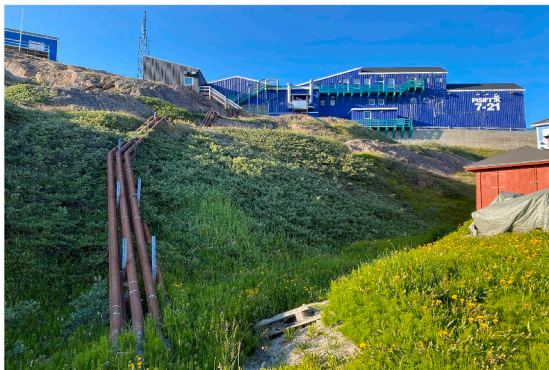


Fig. 14. Integrated district heat networks supplied by fish waste, trash, wind power, and solar power in Sisimiut Greenland.

feasible options [92].

A major finding from our research, focus groups, interviews and field survey is that datacenter operators have no incentive to invest in infrastructure to support heat reuse. Additionally, the heat generated may not be significant when compared with the scale of heating required for major cities. However, as datacenters increase their footprint and

computational utilization, they can be pooled in form of virtual heating plants to supply cities and districts. Forward looking policy initiatives from national and municipal governments should include redefining zones and building supporting infrastructure that anticipates the growth in datacenter footprint. This way it would become easier to mandate that datacenters integrate into existing regional or district heating networks.

5.5. Integration of renewable energy

The integration of renewable energy encompasses another class of solutions. This can include onsite generation from onsite renewables such as solar power (see Fig. 15), with no requirement for grid transmission or transportation, or onsite generation from offsite renewables such as hydropower (see Fig. 15), which need grid distribution and some potential transmission. Or it can include offsite generation, which would need transmission and distribution, investment in offsite technologies or a power purchase agreement, or renewable energy supply from third parties, purchased through renewable energy credits or green certificates. All four types of renewable energy utilization can be harmonized with cooling supply (via chillers, outside air cooling, or other options in section 5.2) and heat reuse (options discussed in section 5.4). Studies suggest that such integration can reduce both recurring power costs and the use of fossil-fuel energy by as much as 60% compared to non-integrated techniques [93].

Datacenters require a stable and resilient electricity grids to function optimally. This is the major reason why they are connected to the grid. Attempts at integrating renewable energy can start with national policies that incentivize datacenter operators to utilize a mix of renewable energy technologies including onsite storage to displace non-heating and non-IT needs. National policies can also propose mandates that encourage load sharing (or hybridization operations) between the existing grid and the onsite system in datacenters. This can follow an incremental pattern to prevent significant distortions to the existing landscape in the event of a fault.

A. The 45 MW Buksefjord Hydro Plant



B. Integrated solar energy production in Nuuk



Fig. 15. Low-carbon sources of electricity supply in Greenland.

5.6. Green disposal and waste

These solutions all relate to disposal and waste handling. Old computers, servers, and mainframes can potentially be reused or refurbished, or recycled at the end of their useful lifetime. Flows of electronic waste need to also be carefully managed to avoid being a burden on landfills or communities exposed to toxic elements within waste streams [94].

Disposal and waste were also notable as it arose consistently in our expert interviews. Many of the datacenters in the Nordic region actively plan for sustainable management and seek to utilize best practices. NO2 spoke about their own strategy as follows:

We are ISO 14,000 certified. So we've got the environmental part of it, so we have procedures on how to more or less handle batteries when at end of life and currently we have an agreement with a company in Norway that are recycling what could be recycled. They have procedures they're certified and they have everything in order to more or less reuse what could be, the servers to the storage unit and so on. Everything that goes out of our datacenters is being evaluated if it could be reused and we see quite a lot of the server equipment, the hardest and so on, are moved back to the manufacturer as spare equipment, so it's entering into another life cycle [elsewhere].

NO4 also articulated some of the efforts they were making to be more sustainable at their datacenter. As they stated:

We have part of my team sitting in Germany looking closely at sustainability issues. They are responsible for regional market part of the Open Compute project to make sure that we can discuss scope one, scope two and scope three elements of how we can handle IT equipment ... We are dealing directly with those guys to make sure that the datacenter community get more, let's say, aligned to what is important to do when it comes to not only buying the right kind of equipment, but also to make sure it has the longest life time possible and also reuse. So that is something that we are very focused on doing and like I say the community in my hometown here is working with circular economy. So everything related to how to handle the IT load, type of equipment, whether it's infrastructure equipment, or it is equipment related to what goes into the white space. We are focusing a lot on that.

However, such e-waste and recycling practices were not uniformly adopted and G9 admitted that "further improvements can certainly be made."

5.7. Datacenter policy and governance

Our final themed solution has the greatest number of options, perhaps because these all center on policy and governance, and can thus affect all of the other scales mentioned previously in Sections 5.1–5.7. Energy efficiency standards for equipment are one important solution available to make datacenters more optimized, along with tax credits and procurement standards and public funding for research in new designs or management practices. Regulatory compliance, Impact Benefit Agreements, and equitable taxation schemes were all mentioned as ways to enhance community wellbeing or acceptance. Restrictions on cryptocurrency mining were frequently suggested, and local content or employment requirements and ensuring transparent and reliable data about datacenter energy and climate footprints are also promising options.

For example, policy at many levels (city, state, national, regional) can support energy-efficient datacenters by implementing or strengthening standards such as Energy Star for servers, storage, or network devices. These give datacenter operators access to more efficient technologies and can allow for important industry benchmarking, building

on the already established Standard Performance Evaluation Corporation's (SPEC) Power benchmark for servers [95]. Such standard setting and benchmarking could be accompanied by procurement standards, tax credits and other rebates that can further ensure datacenters are incentivized to purchase and install state of the art energy efficient devices.

Public funding for research and development could assist in the innovation and improvement of computers, data storage, communications, heat exchange and removal technologies, and even software. Examples of cutting edge options that could be promisingly supported by greater public funding are liquid and immersion cooling techniques, artificial intelligence for infrastructure management, increased chip specialization, materials for ultrahigh density storage, and quantum computing (to name a few) [96]. Another notable gap in research relates to the detail of the cumulative impact of datacenters now and in future, to offer a more systemic view of impacts that reflects how the industry scales in order to enhance their return on investment, rather than studies that only look at a single datacenter in isolation.

Ensuring regulatory compliance can help minimize the use of datacenters for what G6 called "illicit things that nobody wants, such as datacenters for child pornography, or for illegal online gambling, or to facilitate ransomware attacks, or hacking, or spying." Impact Benefit Agreements (IBAs) can ensure that datacenters in rural communities or remote countries such as Greenland also see communities directly benefit from investment; IBAs are already commonly used in the Arctic resource extraction sector, especially for oil and gas [97]. G2 elaborated on this point:

If we are to bring new datacenters to communities here, we need to do the same as with the mining industry. We need to make a social impact report, make an environmental impact report, and to make an Impact Benefit Agreement. This latter instrument is actually a contract with requirements on how to include local society, protect indigenous peoples, and avoid the benefits from the datacenter becoming enclaved, and benefitting only a few.

A related theme concerned ensuring that datacenters pay adequate taxes and generate revenues for local communities. G2 spoke about how "you want to avoid what happened with McDonalds in Denmark, where they avoided paying taxes at all." Greenland Group 1 was very clear on this preference:

It is really important that datacenter companies pay rent to the government, that you get Amazon or Facebook to actually pay taxes.

Greenland Group 2 also spoke about how "taxing these companies is my top priority, you have to have some kind of digital royalties or strong taxation regimes in place."

Multiple respondents, especially those in all six of the focus groups, questioned the use of datacenters for cryptocurrency mining. Some even went so far as to say such actions should be "made illegal", "banned" or "outlawed." One younger woman in Greenland Group 1 clarified their position as follows:

I don't think they should make cryptocurrency at all. This is so stupid and ridiculous; they need to stop doing it. One cannot eat it or trade it for something you can eat, it's ridiculous to waste infrastructure and energy for this.

Some respondents spoke about setting in place stipulations or requirements that datacenters use local content (such as local contractors, local firms, local materials, or locally sourced computers) or employment. As Greenland Group 1 put it, "local employment is very important, I would want everything from personnel, cleaning, and a cantina, to things around it, even mowing the lawn or sweeping the floors, to be local jobs."

Our final recommendation involves ensuring transparent and reliable information about datacenters. One aspect of this is better quality

data on datacenter performance and open data repositories for things like data center energy use and operation, and resulting environmental footprints. These are moderately established in some Nordic countries, but completely lacking for some (e.g., Greenland) and also lacking for some major datacenter hubs such as China [98]. Similarly, better data and analysis on how to create green datacenters would help inform industry stakeholders and planners. One survey of IT professionals for example found that only about 50% have saved energy through server virtualization, and only one-third have made efforts to improve airflow efficiency. Fewer than 18% made efforts to power-down servers not in use, and only about 10% have tried direct current power or liquid cooling [99]—clearly implying best practices for energy efficiency are not well known or understood.

6. Conclusion

Digitalization and digital infrastructure such as datacenters are a cornerstone of modern society. Policies for a more sustainable digital society can only be driven with a new body of evidence for the co-benefits of more sustainable online services and digital devices. To make informed policy about infrastructural expansion (data centers, fiber-to-the-home) and data-hungry consumer devices (smartphones, tablets, laptops, televisions, smart fridges, self-driving cars), we must come to better account for their energy requirements and flexibility of demand against the very real benefits and threats presented by online services and devices. Co-benefits—which we define as positive spill-overs—include privacy, security, health and wellbeing, enrichment of social and private life, access to public services and subsidies, and civic participation.

Although renewable energy and energy efficiency measures can meaningfully reduce onsite energy use at datacenters, this depends upon managers investing in costly state-of-the-art technology or connecting to already established low-carbon grids. Our study however reveals that many datacenters operating in the Nordic region do not adhere to best practice, are not maximizing power utilization effectiveness, nor are they adequately capturing indirect or embodied emissions related to datacenter design and construction, disposal, or electronic waste. Our focus groups and interviews indicate a good level of public and stakeholder support for datacenter development in the Nordics, but also a concern about energy consumption, especially in relation to cryptocurrency mining.

Datacenter operators, and policymakers and planners, need to promote a broader, more holistic notion of sustainability that extends beyond servers and computers to encompass the whole system. Although this broadens the challenge of datacenter sustainability, it also enables the identification of a multitude of options to ensure future digital services are more affordable and resilient but also more energy-efficient, more climate friendly, less wasteful, and more optimized. Whether our digital future degrades communities and natural systems, or helps decisively dematerialize societies and decarbonize activities, remains to be seen.

Credit author statement

Benjamin K. Sovacool: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Chukwuka Monyei and Paul Upham: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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